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Packet Radio Temporary Note No. 56

Packet Radio Note: A Measurement Program for Packet Radio Channel Characterization

I BACKGROUND

Many new or previously untried concepts enter into the development of a full-scale packet radio network. Among the first questions that must be resolved are those basic to the ability of a wideband system--such as packet radio--to operate in an urban/suburban situation. This environment may be inimical to the packet radio network from two standpoints:

- The impulsive man-made noise radiated from power lines from automobile ignition systems and from other sources may cause high packet error rates.
- The existence of many radio-reflective surfaces, such as buildings, in the vicinity of a receiver may result in unacceptable multipath.

The published literature does not provide adequate information to determine the effects of impulsive noise and multipath upon the packet radio network; thus, answers to these questions must be sought in a measurement program.

The plan is to perform the necessary noise and propagation measurements for the packet radio network in the actual urban and suburban locations that will serve as points in the packet channel test system, thereby ensuring the applicability of the measurements to the later experimental situation. It is intended that much of the equipment used in the initial measurement program will be smoothly integrated into

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an eventual channel test facility. In particular, a mobile lab vehicle, needed to contain the measurement equipment, will, along with its power generator, antennas and test equipment, be phased into the test facility as a mobile terminal or perhaps as an interim repeater. A judicious selection of the minicomputer to be used as a part of the data-acquisition system will allow this same machine to be used, after the completion of the first year's measurements, as the controlling computer at a packet repeater site or as a data-collecting and processing unit for further link tests.

The measurements to be made in the first year are those pertaining to the noise environment and those concerning the propagation path. They will be made at typical urban, suburban, and rural locations, and near the two candidate frequencies (approximately 400 and 1500 MHz) at which the packet radio network may operate. The receivers (and transmitters for propagation measurements) are to be provided by ARPA and integrated by SRI into a data-acquisition system. As mentioned, this system will be housed in a van containing a power generator; the van will also contain a minicomputer for control and data processing, and other test and maintenance equipment.

Both the noise and propagation measurement programs will be designed to provide results useful not only to packet radio but to other urban radio systems as well. SRI plans to publish the results for wide distribution, as they will extend the knowledge of the urban/suburban radio channel.

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II QUANTITIES TO BE MEASURED

A. Noise

At the locations and at the frequencies that a packet terminal or relay is expected to operate, the major sources of radio noise are the highly impulsive incidental radiations from man's activities and equipments. Terminal locations can be expected to be fully immersed in this noise environment. Preliminary measurements by SRI at 400, 1200, and 2900 MHz indicated that automobile and other man-made noise was almost always present at the lower frequency and less likely as the frequency was increased. The 2900 MHz frequency was relatively very quiet but the impulsive noise greatly increased when automobiles passed by.

If we suppose that an error in any bit within a packet will cause a packet error and that only noise impulses cause errors, then we can estimate the packet error probability in terms of three parameters. These are: (1) P_{PA}, the conditional probability of a bit error given that a pulse in the packet exceeds amplitude A, (2) P(A), the pulse-peak amplitude density and, (3) $P_{iA}(t)$, the density of pulses exceeding amplitude A during a packet duration t. The equations below indicate how the parameters are used to estimate the packet error probability, P_e.

$$P_e \triangleq \Pr\,[\text{noise-caused packet error}] = \int_0^\infty P_E(A)\,P(A)\,dA$$

where

$$P(A) = \text{the density of pulse-peak amplitudes}$$

and

$$P_E(A) = \Pr\,[\text{one or more bit errors} \mid \text{pulse amplitudes } A].$$

Now we define

$$P_{PA} \triangleq \Pr\,[\text{bit error} \mid 1 \text{ pulse in time } t \text{ exceeds } A]$$

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and, extending this to i pulses in the packet,

$[1 - P_{PA}]^i$ = Pr [one or more bit errors | i pulses in time t exceed A].

We now define the new parameter

$$P_{iA}(t) \triangleq \Pr [\text{i pulses in time t exceed A}]$$

and, summing over all values of i, we obtain

$$P_E(A) = \sum_{i=0}^{\infty} P_{iA}(t) \left[1 - (1 - P_{PA})^i\right] .$$

Finally;

$$P_e = \int_0^{\infty} \sum_{i=0}^{\infty} P_{iA}(t) \left[1 - (1 - P_{PA})^i\right] P(A)\, dA$$

so that it appears that we can estimate the probability of noise-caused packet errors in terms of two measurable parameters, P(A) and $P_{iA}(t)$, and the one system-dependent parameter, P_{PA}. The last parameter cannot be measured immediately although an analytical approach may yield acceptable results for the time being. Later, when we have an experimental packet system in the field, we may be able to make actual measurements of P_{PA}.

In addition to these pulse measurements, we will also measure the two most universally useful basic noise parameters. These are the mean noise power and the ratio of rms to average noise voltage, which is a measure of the "impulsiveness" of the noise. Both have been widely measured for atmospheric noise and are coming to be recognized as useful in the area of man-made noise also.

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B. Propagation

To adequately characterize the packet radio channel we must add a set of propagation descriptors or models to the noise parameters already mentioned. Most obviously a knowledge of attenuation rate must be obtained to determine areas of coverage for certain radiated power levels and antenna heights. Furthermore any useful description of the channel must eventually relate to the possible distortion a packet may suffer in proceeding from antenna to antenna.

A review of previous material concerning propagation in the .5 and 1 GHz bands reveals that some of this information exists--particularly regarding the use of these bands in the land mobile service. Of the needed information, that concerning field strength as a function of distance for various terrain conditions is the best defined. The extensive model of Okumura et. al.( ) appears adequate for our purposes and is in substantial agreement with other investigations( ) some of which are quite recent( ). The Okumura model was derived from measurements and spans the frequencies of interest to packet radio. Because of the wide variety of possible terrain (e.g., the degree of urbanization) in which packet radio terminals may operate, we intend to compare some amplitude data against the Okumura model--if for nothing else than to associate different environments with the model.

As mentioned earlier we anticipate the need for characterizing the channel in terms relevant to very wide-band signals. To this extent available information is somewhat limited( ) and in some instances does not exist at all. All of the parameters we state below as needed for adequate channel characterization relate to the RF signal design.

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A review of previous material concerning propagation in the .8 and 1 GHz bands reveals that some of this information exists--particularly regarding the use of these bands in the land mobile service. Of the needed information, that concerning field strength as a function of distance for various terrain conditions is the best defined. The extensive model of Okumura et. al.( ) appears adequate for our purposes and is in substantial agreement with other investigations( ) some of which are quite recent( ). The Okumura model was derived from measurements and spans the frequencies of interest to packet radio. Because of the wide variety of possible terrain (e.g., the degree of urbanization) in which packet radio terminals may operate, we intend to compare some amplitude data against the Okumura model--if for nothing else than to associate different environments with the model.

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We intend to treat the channel as a linear filter which, in the case of fixed terminals, is probably not significantly time varying. Time invariance is presumed principally because the expected Doppler shifts are small relative to the allowable phase-variation over the detection period (approximately 10 μsec.). Our first attempts, however, will be directed toward determining whether or not motion of multipath reflectors is significant. This concern stems from the possibility that rapidly moving reflectors such as aircraft may be important. Even if they do not become important to packet radio, the effects of lower velocity reflectors such as automobiles will nevertheless be documented.

While the importance of time variability may be questioned for this 100 kbps channel, the limit on coherent bandwidths due to multipath is already well documented. We shall attempt in this program not only to determine the amount of excess delay due to multipath but also some of its shape characteristics that will be important to possible time delay capture properties of wide band signals.

In considering the type of modulation to be used in the propagation measurement two choices become apparent: 1) a modulation with low ambiguity in both time delay and Doppler shift or 2) two separate modulations each having good ambiguity properties in one of the respective dimensions. We have chosen the latter for three reasons. First, the real-time on-site digitization of a wideband signal with low ambiguity in both dimensions requires rapid A/D conversion together with direct memory access into the computer--a somewhat elaborate and

expensive hardware and software problem. Second, the information available from treating the two dimensions separately provides all the information necessary for communication system modeling--namely a measure of spread in time delay and in frequency. Third, we fully expect the channel Doppler characteristics to be of little consequence to the high data rates contemplated for packet radio.

We therefore intend to measure each of the following quantities for both frequencies and for various categories of terrain:

1. The distribution of maximum excess delays (i.e., beyond free space) for various terrain characteristics. This is needed to guide the selection of the maximum bit rate that avoids intersymbol interference. As indicated in Figure 1, this quantity will be given parametrically in amplitude levels below the peak value. A second important excess delay measure is time delay spread. This is defined as the second central moment of the impulse response and is perhaps the must useful one-number characterization of time delay for error probability estimation.

2. The shape of the multipath delay. This is essentially the impulse response of the channel but more particularly an attempt to quantify the resolvability of individual multipath components. Results will be given in terms of plots such as those in Figure 2. Resolvability as indicated in this manner will be explored at RF bandwidths of 20 and 40 MHz.

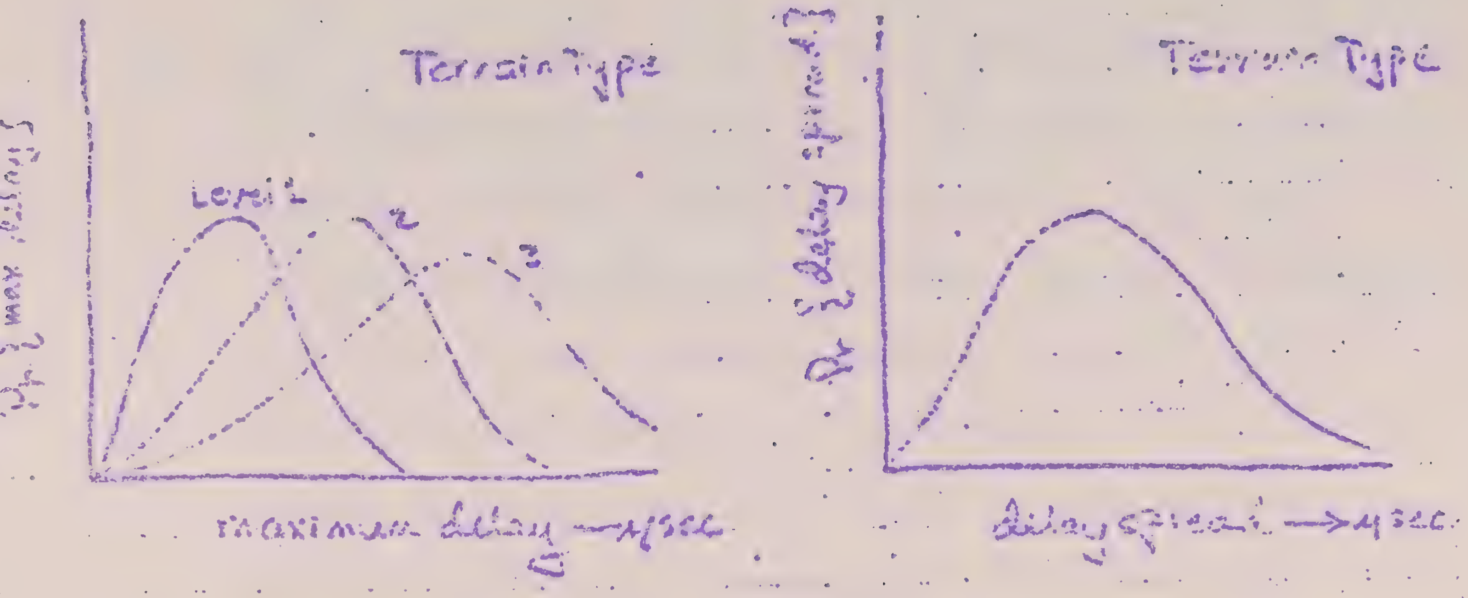

Fig 1. Maximum Delay and Time-Delay Spread

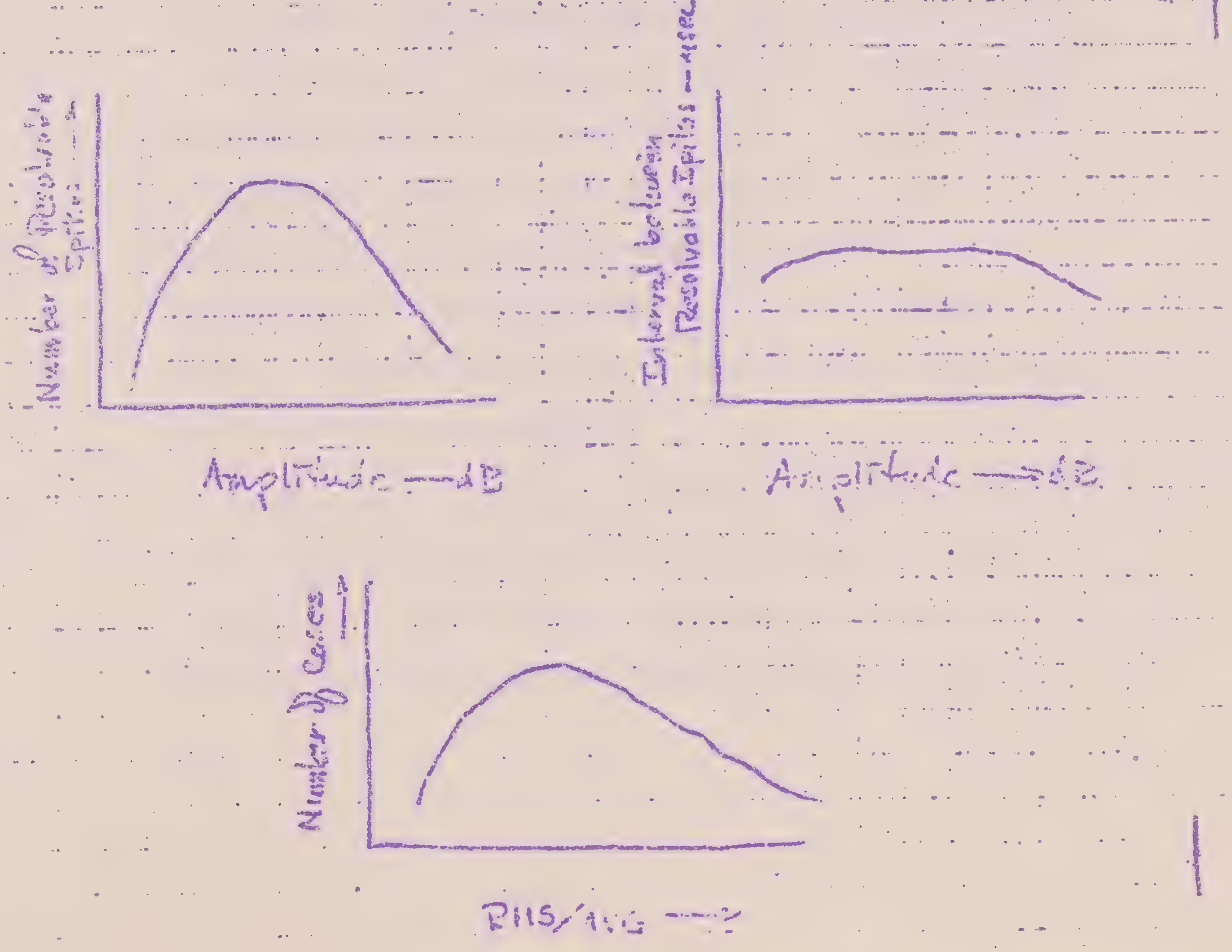

Fig. 2 Descriptors of the Shape of the Impulse Response

3. The time variability of the channel. This measurement will be approached from two standpoints: (a) what is the Doppler spectrum at frequency shifts less than ±100 Hz which most multipath targets are expected to cause, (b) what is the Doppler spectrum at frequency shifts approaching those that would affect a 100 kbps DPSK system. These will, of course, require different bandwidths but in both cases the variability will be given in terms of power spectra similar to that shown in Figure 3.

4. The spatial variability of the channel. This measurement, important to mobile terminals, is perhaps best defined in terms of systems that can or cannot resolve multipath. For those that cannot, a narrow band recording of a spatial frequency spectrum will be able to describe the Doppler spread for any given vehicle velocity (see Figure 3). The measurement will be made by driving the mobile terminal at a constant velocity (governor controlled) while recording the output of a narrow band quadrature detector also used in the time variability measurement.

For a system that does resolve multipath, the wideband signal will be used to track individual multipath components as the vehicle moves. This may be done incrementally by digitally recording the received pulse at specific points in space.

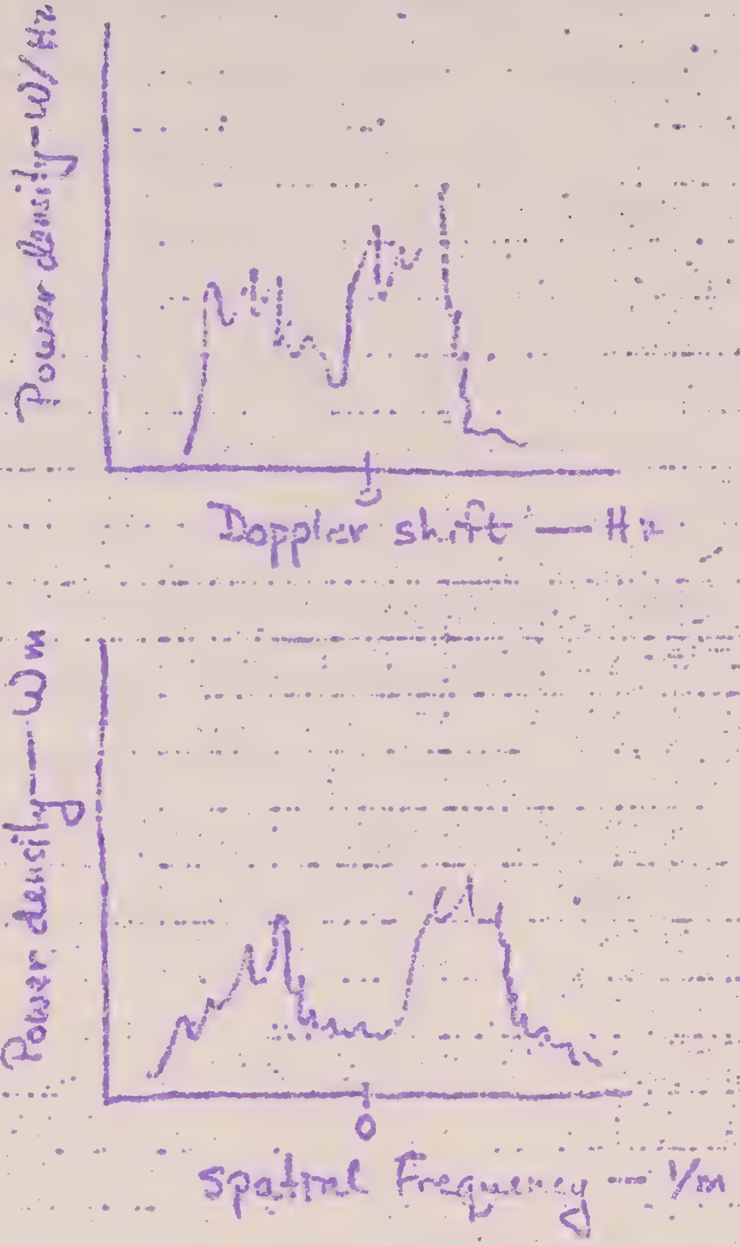

Fig 3. Doppler and Spatial Frequency Spectra

5. Effect of Directive Antennas

Directive antennas are normally thought of as able to reduce either required power levels or interference. In this instance we would propose to explore their use in reducing multipath spread. A receiver located in a highly reflective urban environment will probably receive multipath components from a wide range of angles. To reduce the number of those components in azimuth, it will perhaps be adequate to judiciously place a null as opposed to trying to obtain directive gain. This approach would be exploratory since it is not clear that for terminal-to-relay communications (or the reverse) directive antennas are useful. Elevation patterns can be made narrower than the normal vertical monopoles both to conserve power and to some extent to reduce noise. This also will be explored.

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III. MEASUREMENT LOCATIONS AND RANGES

A. Noise

Noise measurements in support of packet radio should be made not only at all the urban and suburban locations that are logical choices for the measurement of the propagation path characteristics but under some additional circumstances also. Although there may be little reason to suppose that the gross multipath characteristics of a particular path would change appreciably during the period of a day or a few hours, man-made noise is highly variable over these times. Within a city, for example, we have observed a considerable increase in the noise, identifiable with the passage of greater numbers of automobiles during the commuting periods. We expect the urban noise environment to differ greatly from day to night, requiring measurement at intervals around the clock to characterize the urban packet radio noise. Further, since the noise at the frequencies considered for use by packet is generally man-made, we may expect to find a work-week dependence within urban areas that would not exist for naturally-occurring noise processes. Weather conditions are also an important variable for radio noise originating from high-voltage power transmission and distribution lines. Foggy or damp weather has been observed to raise the average noise power from power lines by more than 20 dB over that measured under dry conditions. To the extent that the aggregate urban noise is composed of that from power lines there will be a weather dependency in the urban noise environment.

So far we have suggested the measurement of noise only at those locations that are being considered for propagation measurements,

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but for additional times. Now we suggest some further noise measurement locations, selected to isolate particular noise sources rather than to accept the aggregate noise of the urban/suburban environment. To help relate these noise measurements to others, we plan to seek out and to measure the noise from a power line in an isolated area where there are no other noise sources and to similarly measure the noise near a freeway where the automobile ignition systems will be the only noise sources.

Table I will summarize the noise measurement situations that are being planned.

Table I

NOISE MEASUREMENT SITUATIONS

Location	Times	Other Conditions
Urban/Suburban	Intermittently for 24 hours	
Urban/Suburban	Intermittently for 4 weeks (including week-ends)	
Urban/Suburban		Wet and Dry Weather
Isolated Freeway		Heavy and Light Traffic
Isolated Power Line		Wet and Dry Weather

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B. Propagation

The locations at which propagation measurements are necessary are those which are categorical. That is, they constitute a differentiable set that would apply to a wide range of packet radio operating environments. At this time we anticipate that packet radio terminals and repeaters will operate mostly in urban/suburban environments, which in many respects may constitute the most challenging operational environment. We will therefore concentrate on that type of "terrain" using various points in the San Francisco Bay Area.

Since determining signal strength contours about a given transmitting antennas will not be our primary emphasis (observed strength will be checked against existing models, however), locations will be chosen first on the basis of expected multipath severity and the liklihood of direct line-of-strength propagation. An example of one categorization is given in Table II where for completeness a rural class is also included. Possible locations in the Bay Area satisfying these categories are indicated in Table II and on Figure 4.

Propagation ranges or areas of coverage used in this measurement program are intended to be of the order of those contemplated for packet radio. Since the coverage area, as far as equipment is concerned, is defined by the transmitter energy per bit and the relative antenna height, we will be using power levels, modulation types, and antennas similar to those proposed for the early packet radio systems. Depending upon the type of terrain and relative antenna heights, coverage radii of between 5 and 40 km are anticipated.

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Table II

CATEGORIES FOR PROPAGATION MEASUREMENTS

Category	Type of Propagation: Loss	Type of Propagation: In Defilade	Map Location
Dense Urban More than 20-story building		X	A
Moderate Urban 3 to 20-story buildings			
Hilly	X	X	B
Flat	X	X	C
Moderate Urban Geographically limited	X		D, E
Suburban			
Hilly		X	F
Flat	X		G
Rural			
Hilly		X	H
Flat	X		I

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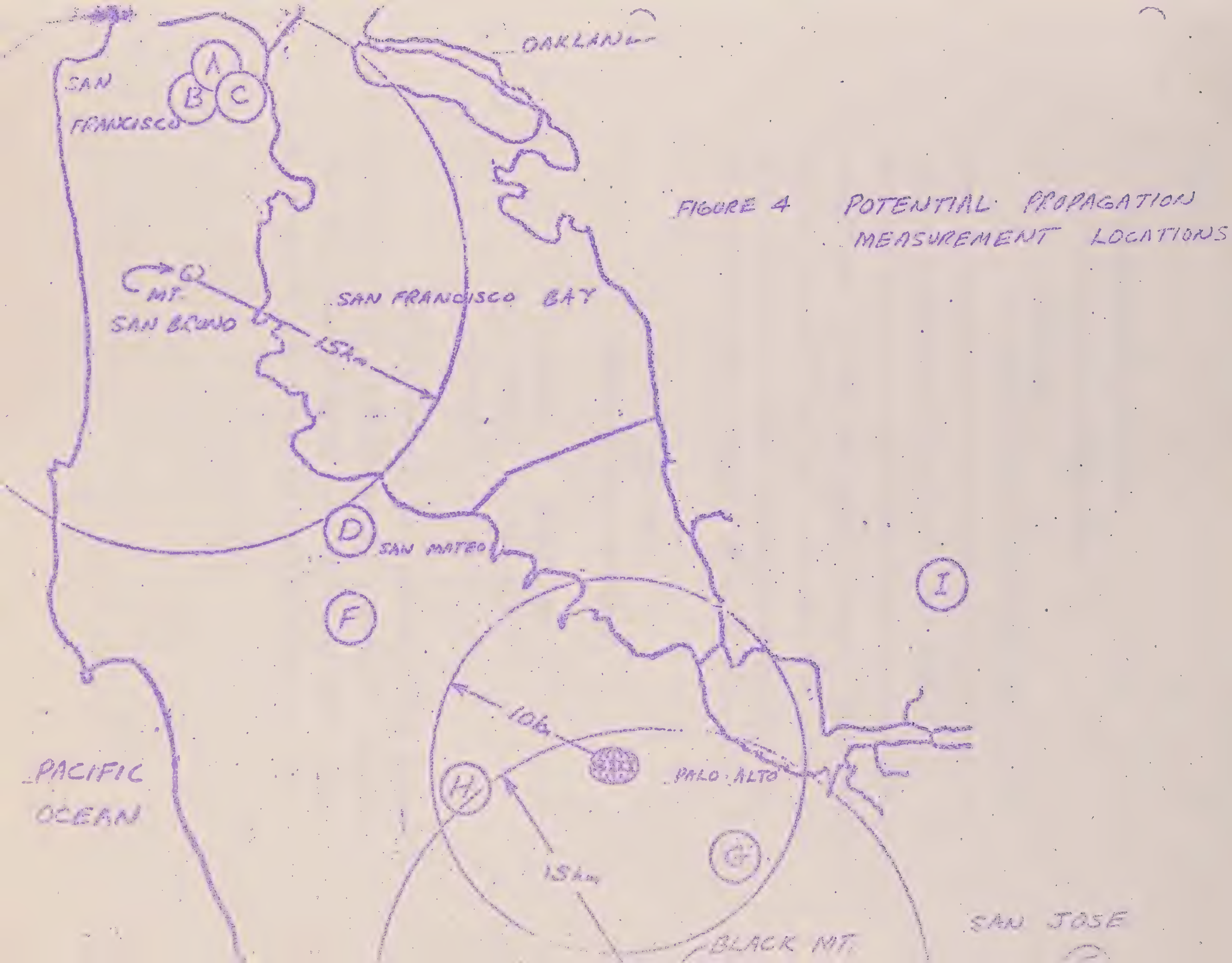

FIGURE 4 POTENTIAL PROPAGATION MEASUREMENT LOCATIONS

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IV INSTRUMENTATION AND PROCESSING

A. Radio Frequency Instrumentation

1. Transmitter

The transmitter must be of sufficient power and the antenna of sufficient height to provide the coverage needed over the distances characteristic of the test area. These distances, a few of which are shown on the map of Figure 4, are typical of those expected in packet radio. Using the curves given by Okumura,( ) transmitting and receiving heights of 20 m and 1.5 m, respectively, unity antenna gains, and the requirement for at least a 20 dB signal-to-noise ratio, the power requirements stated in Table III are adequate for a nominal radius of 10 km.

Table III

TRANSMITTER POWER REQUIREMENTS

Frequency	Average Power
500 MHz	4.8 dBm or 3 mW
1500 MHz	18.4 dBm or 70 mW

The block diagram of the transmitter is shown in Figure 5. The transmitter will be switchable between CW and pseudo-random-pulse operation. All oscillators will have a stability of at least a part in 10^{10} such that a resolution of .5 Hz may be obtained at 1.5 GHz.

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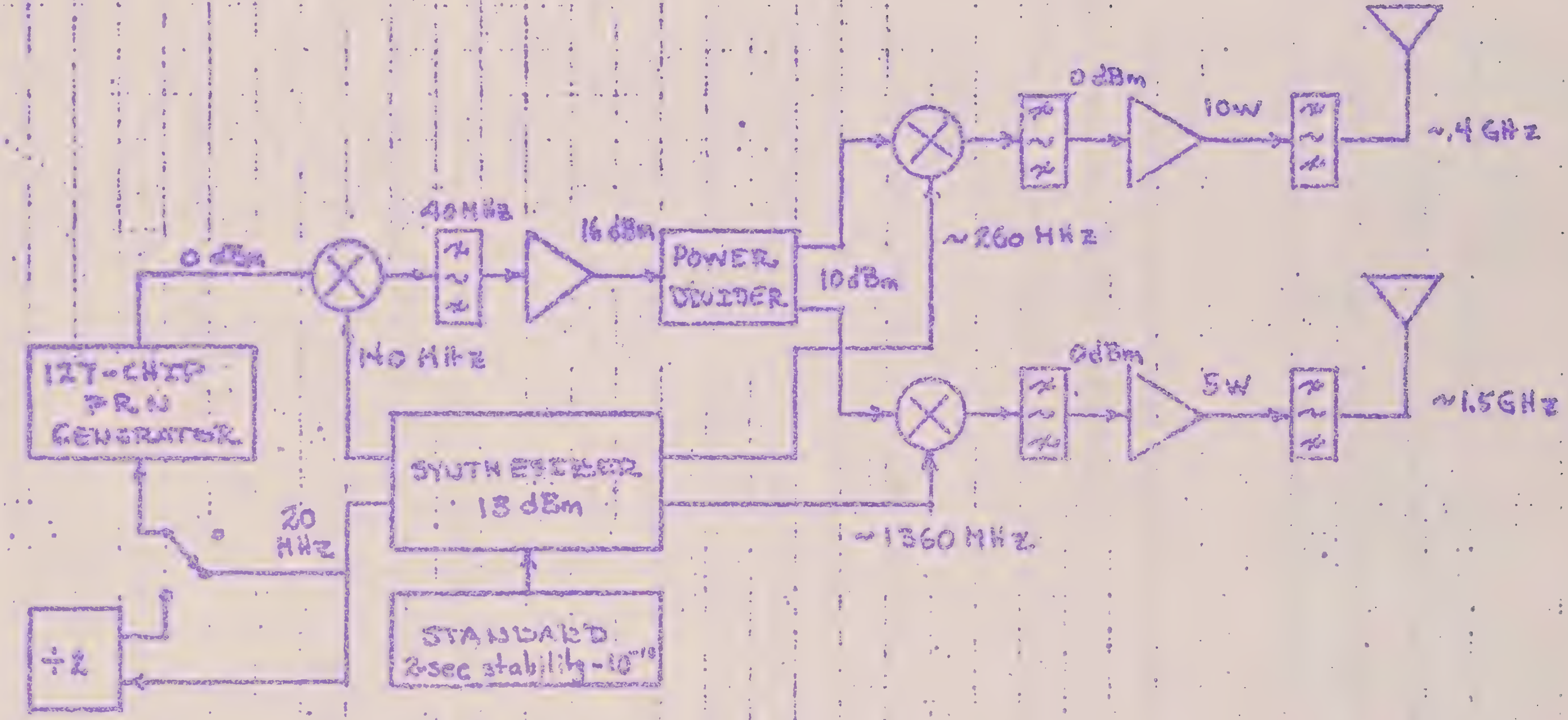

Fig. 5. Transmitter System

Operation of the transmitter will probably be manual in the sense that switching between various frequencies and bandwidths or between on and off will be by hand. The transmitter equipment must be easily portable since it will be sited temporarily at several different locations.

Transmitting antennas will be omnidirectional in azimuth. Vertical beamwidth may be narrowed below that of a vertical dipole particularly since the transmitter antenna is to be elevated.

2. <u>Receiver</u>

As will the transmitter, the receiver will consist of separate RF sections for the two frequencies (see Figure 6). Manual switching will occur at the 140 MHz IF. Branching for the various noise and propagation measurements occurs following a linear IF amplifier. The dynamic range at this point should be greater than 60 dB. All oscillators must be stable to at least one part in 10^{10}.

a. <u>Noise</u>

Noise will be measured in bandwidths of 40 MHz and 200 kHz. The switch-selectable 200 kHz filter will have unity gain at center frequency. The envelope detector provides, through an output amplifier, a 0-5 V signal.

b. <u>Spread Spectrum Signal</u>

Two 127-chip surface wave devices for 20 and 10 megachip rates will be provided and are to be switch-selectable. The output of each is passed through an envelope detector and an output amplifier with a 0-5 V range.

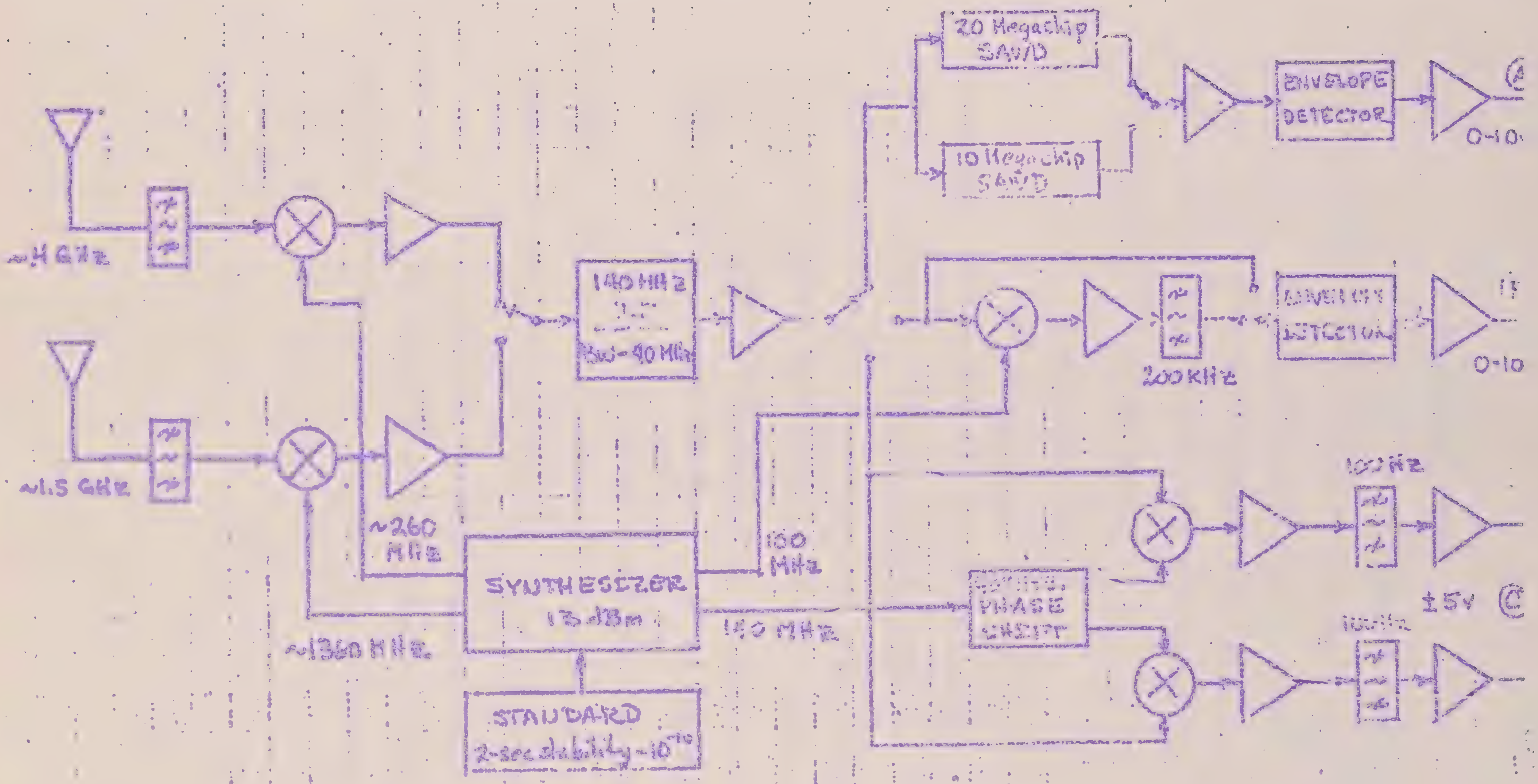

Fig. 6. Receiving System

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c. <u>Narrowband Signals</u>

To determine the extent of channel variation a quadrature detector with two sets of post detection filters is required. One set, with a nominal 100 Hz bandwidth, is intended to portray the spectral region where most variation is confined. A second set, with 5 kHz bandwidth, is for assessing the channel variation in the spectral region of interest to 100 kbps data.

d. <u>Receiving Antennas</u>

Receiving antennas may be directive in two ways. For multipath reduction it may be adequate to manipulate a single null such as that formed by a cardiod. (Because of the small surface available on the mobile van, a large aperture antenna is not feasible. A larger, more directive antenna however, may be part of a fixed packet radio terminal.) If signals propagate predominantly <u>along</u> an urban street, then a null may help reduce the signals from one direction.

A second use of directivity is to minimize the low-angle, nearby sources of noise or interference. This effect requires a vertical lobe that "cuts-in" at low-arrival angles.

Both of these antenna patterns will be used from time to time during the course of the measurements. Their use will probably be restricted to that sufficient for a comparative analysis with more conventional dipolar antennas.

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3. Voice Channel

Since the experiment is not intended to function automatically, a duplex voice channel will be needed to coordinate the activities at transmitter and receiver. Since for each frequency the functions to be performed at the transmitter involve only three states (on with 20- or 10 MHz bandwidth and off), some type of remote relay control may be used.

B. Post Detection Processing and Recording

The processing and recording system proposed in this measurement program is centered around a minicomputer. The timing will be under the control of an external clock whose phase can be set to synchronize with the transmitter.

The minicomputer and timing system are to be time-shared among the particular noise or propagation measurements. The experiment has been designed to maximize the equipment used in common by the separate measurements. Setting up for a given measurement will entail manually switching in of the correct complement of hardware and, through the computer terminal, loading of the correct software. One of the several specific detector outputs shown in Figure 6, in combination with the appropriate peripheral devices, constitutes the processing and recording system for a given measurement. The various arrangements will be described in the following two sections.

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1. Noise

a. Overview

The noise measurement system as discussed here begins just after the envelope detector and includes an amount of special equipment, among which is a minicomputer. This machine is not dedicated to the noise system but is block-time shared with the propagation measurement system. Nonetheless, from the standpoint of either system the minicomputer with its programs for either noise or for propagation may be considered an integral part of that system.

The noise measurement system will have two primary components, an impulse-counting portion and an analog-to-digital portion. They will operate in a time-interleaved manner with the minicomputer servicing each portion alternately for about half the time. A period during which data from both portions is obtained is 20 ms. Interleaving the sampled and digitized noise measurements with the noise pulse measurements, will provide essentially simultaneous statistics of the two types. Due to the rate at which man-made noise characteristics change (as a noisy car passes, for example) data of two types taken in this way are more likely to be representative of the same noise situation than if several minutes of data were collected sequentially with each system. Figure 7 indicates how the two data acquisition systems are to time-share the receiver under control of the minicomputer. The minicomputer will accomplish the small amount of data processing involved and output the reduced data onto the teletype terminal.

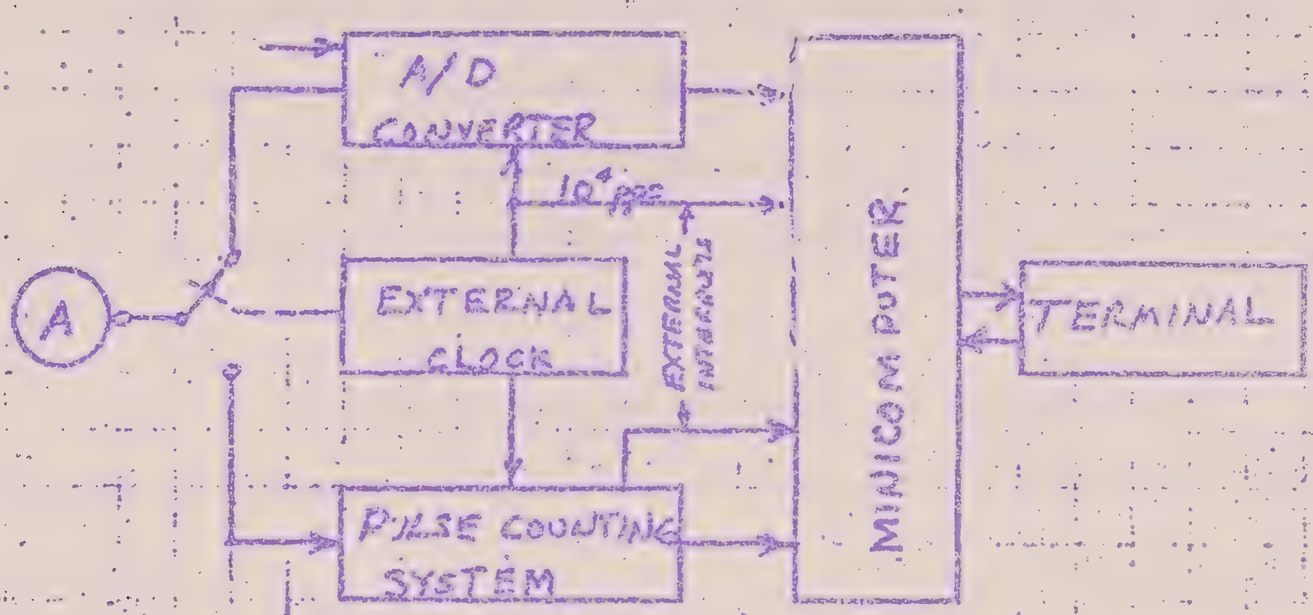

Figure 7

CONCEPTUAL DIAGRAM OF NOISE PROCESSING SYSTEM

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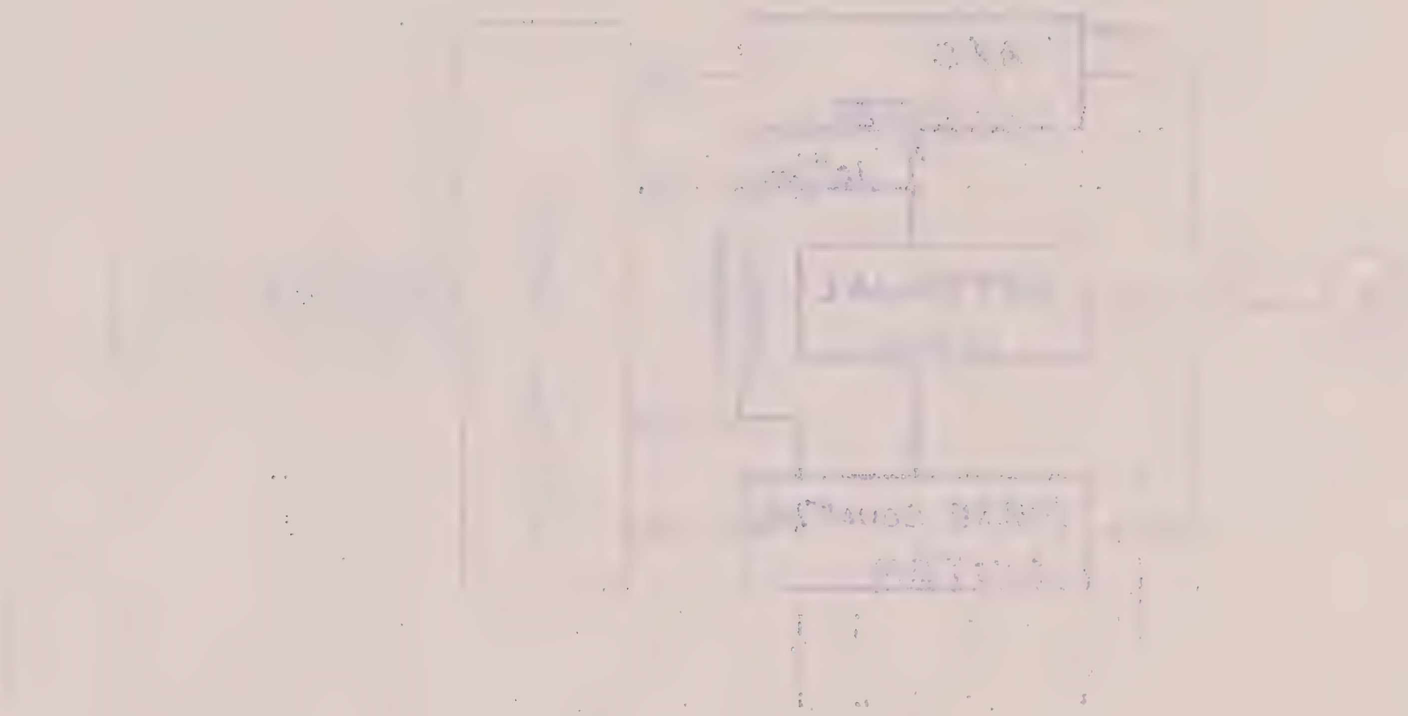

We plan a basic noise data collection period of ten minutes, during which time we will collect data at one frequency at one bandwidth. There will be two frequencies--around 400 MHz and around 1500 MHz--and two bandwidths typical of those at which packet radio may eventually operate--about 40 MHz in the case of spread-spectrum modulation and about 200 kHz in case the spectrum is not spread. Forty minutes of actual noise recording will thus be required to measure the noise at both frequencies and for both bandwidths. There will be, in addition and according to our experience with previous measurement projects, an equal or greater amount of time spent in system calibration and adjustment so that an entire noise measurement will probably take an hour and a half or so.

We now proceed to discuss the two relatively independent noise measuring systems and the timing to tie them together.

b. Impulse Counting

The two noise impulse parameters, $P_{iA}(t)$ or the number density of pulses exceeding amplitude A during a time duration t, and P(A), the pulse-peak amplitude density, will be obtained by means of counts of pulses exceeding certain amplitude levels.

The pulse measurements will require, following the receiver detector, a set of threshold detectors adjustable so that the lowest threshold is exceeded by all of the noise impulses* and the

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* This method defines any positive crossing of the lowest threshold as a pulse. It may be that the level of the lowest threshold should be set in relation to the mean signal or the mean noise level.

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highest is almost never exceeded. A dynamic range out of the detector of 40 to 50 dB is needed although a greater dynamic range would be desirable. We will require about ten thresholds.

To obtain the impulse amplitude distribution we will count the noise pulses that exceed each threshold. After collecting data for several minutes, dividing the total counts at each threshold by the pulse count in the lowest threshold and subtracting that from one will give the noise impulse amplitude distribution. It is currently planned to also count the pulses above each level during each successive second and to ingest that count into the computer for use in computing statistics such as the mean and standard deviation of pulses per second (which will help us to relate our measurements to the measurements of others). If we also retain the time-sequence of pulse counts per second we can examine or process this sequence in search of statistics on the bunching of pulses.

To determine the statistics of the number of pulses occurring in short time-durations, such as the duration of an individual packet, we must either construct a separate counter for each time duration at each amplitude level or else use the computer to read the accumulated count of a single counter at each of the required time intervals. We currently plan to use this first method and to use time intervals of 1, 3, and 10 ms.

The computer is to contain an array C of dimensions L x N x I where

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L = the number of noise amplitude levels (possibly 10)

N = the number of time intervals (probably 3), and

I = the number of pulses per time interval (0 through 1000?)

and where $C(k, n, i)$ is the count of the number of times that i pulses have exceeded the level k per nth time interval. For example, if in a given 10 ms interval ($n = 3$) seven pulses exceeded the fourth amplitude level ($k = 4$), the value of $C(4, 3, 7)$ would be incremented by one. When the ten-minute data collection period is complete the contents of the array can be manipulated to yield various statistics, including but not limited to $P_{iA}(t)$.

c. <u>Impulse Count Equipment and Timing</u>

Our noise-pulse measuring concept is to observe the envelope-detected output of the receiver with a comb of perhaps ten level detectors, three of which are indicated in the sketch of Figure 8. A level detector puts a pulse out each time its threshold is exceeded;

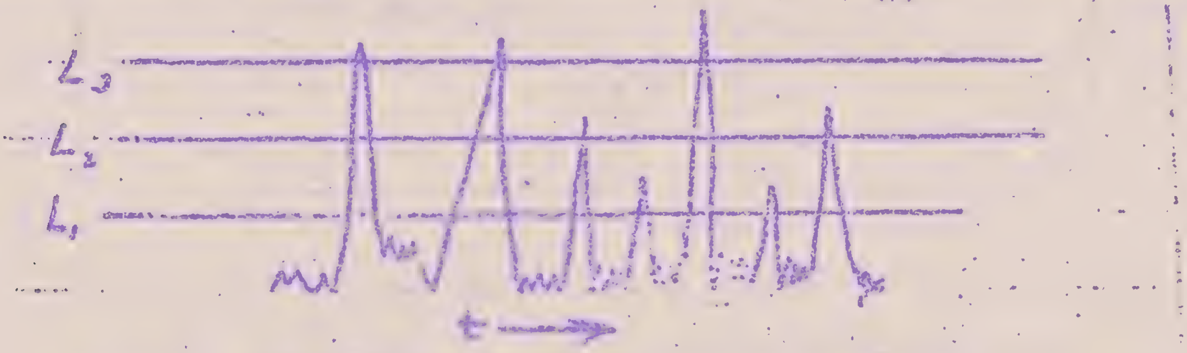

Figure 8 NOISE SIGNAL WITH THRESHOLDS INDICATED

here L_3 puts out 3 pulses, L_2 puts out 5, and L_1 puts out 7 during the time shown. Each level detector module will be identical and so it is necessary to describe only one of these modules. Figure 9 is a block diagram of the impulse measuring system, with one of the modules

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[illegible] time intervals [illegible]

[illegible] number of pulses per time interval [illegible]

[illegible] is the mean [illegible] k per unit t [illegible] interval (n = 1) [illegible] the value of C(d), [illegible] collection period [illegible] integrated to yield [illegible]

[illegible]

The pulse-height [illegible] output of the [illegible] each of which are indicated [illegible] detector puts a pulse out [illegible]

Figure [illegible] with levels [illegible]

[illegible] levels, L_2 puts out 3, and L_3 [illegible] time [illegible] Each level detector module [illegible] identical [illegible] is necessary to describe only one of these modules. Figure [illegible] block diagram of the impulse measuring system, with one of the [illegible]

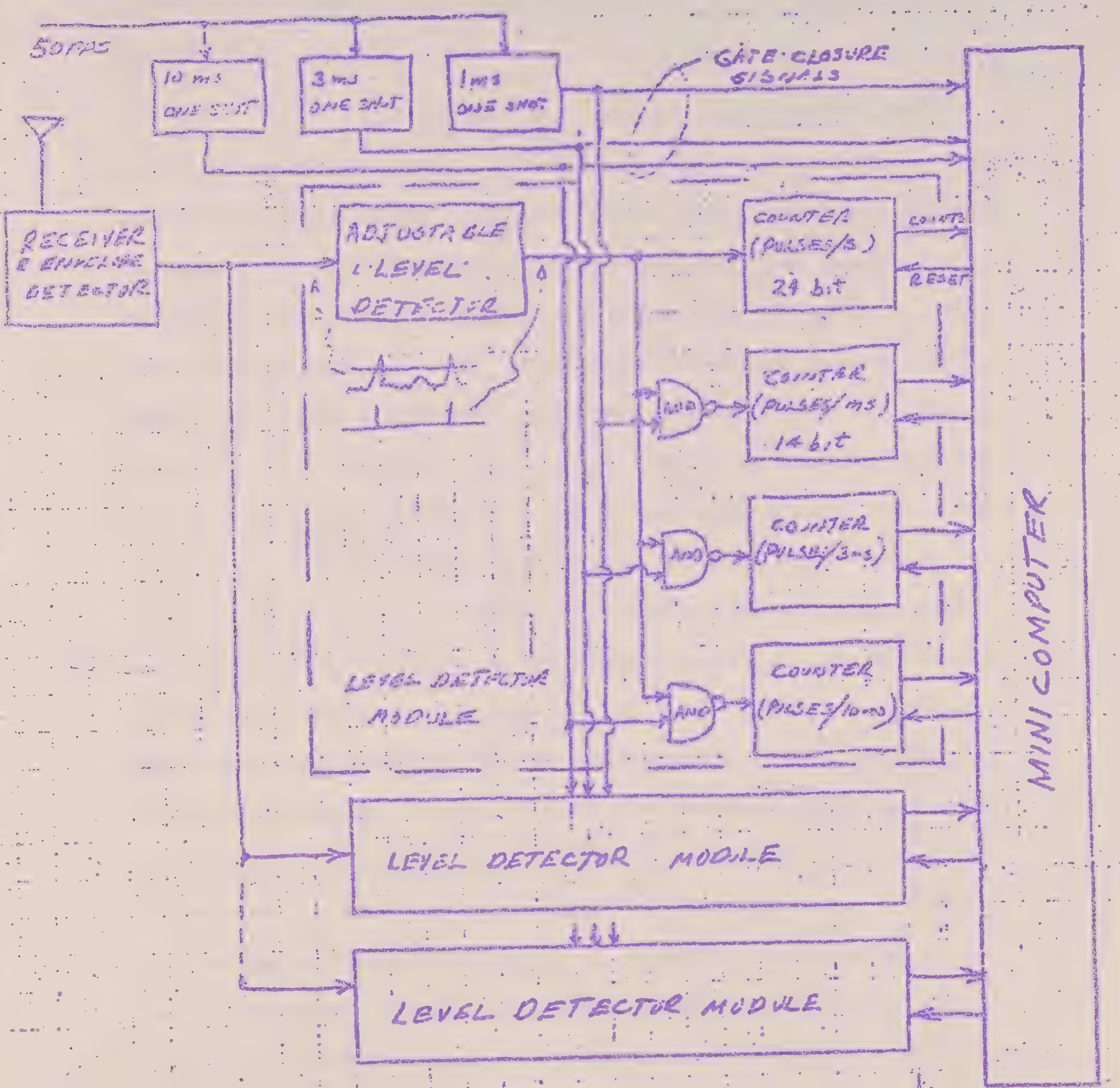
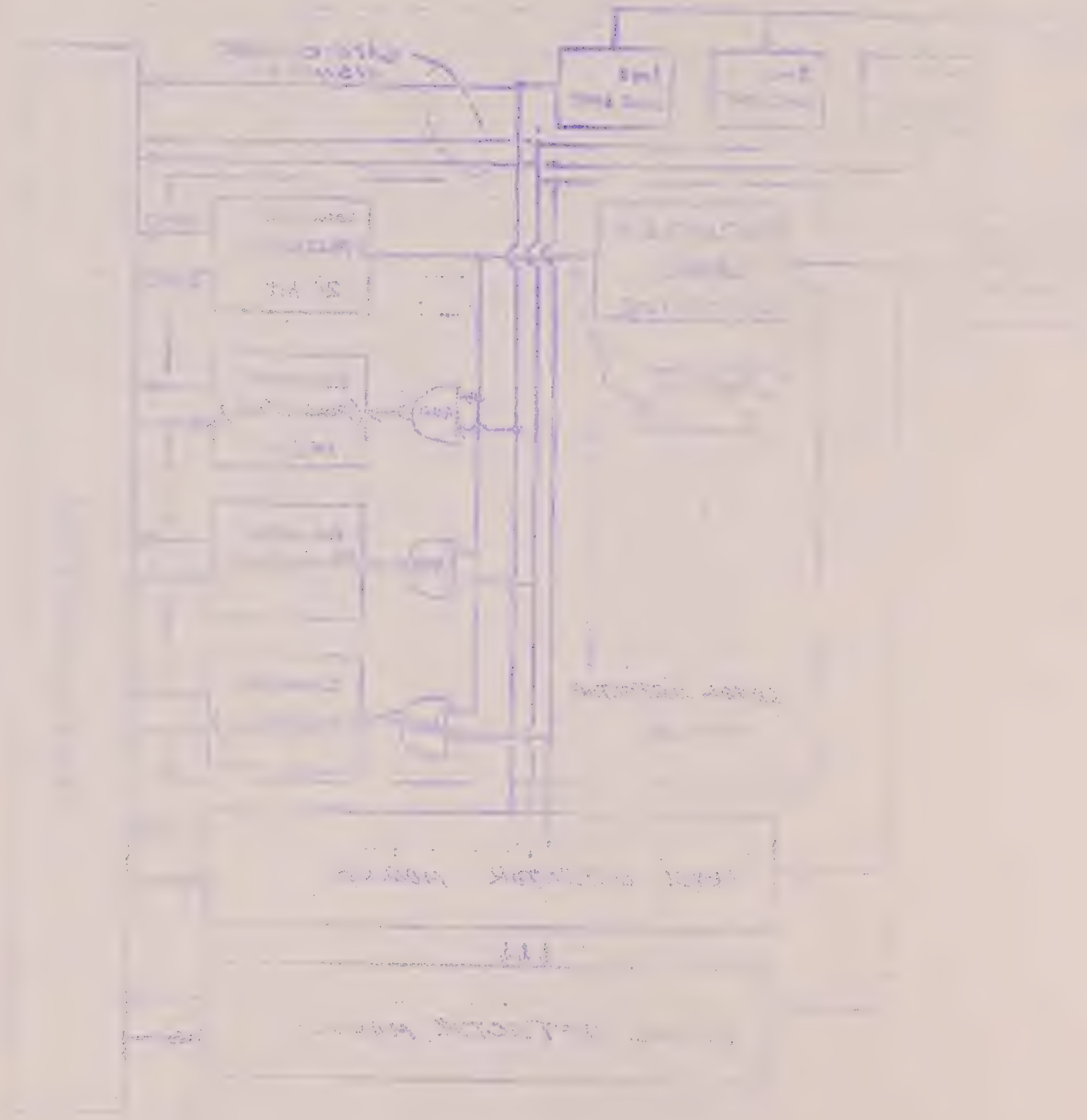


Figure 9

IMPULSE COUNTING EQUIPMENT



shown in some detail and with the others only indicated. Ignored in this figure are both the timing system, which provides clock pulses, and the noise sampling and digitizing system; these are described elsewhere.

The planned level detector module features four counters, one of which counts for a whole second; the other three counters are gated so that they count pulses during brief time intervals. The basic rate of the planned system is dictated by a 50 pps clock, derived from the system's master clock, which opens the gates for each level detector simultaneously. A one-shot then closes the 1 ms gates, another then closes all the 3 ms gates and finally a third one-shot closes all the 10 ms gates. As each set of gates is closed an interrupt sent to the computer will tell it that it may begin reading and resetting the counters. As the timing diagram of Figure 10 shows, the first approximately 11 ms of the 20 ms cycle time is dedicated to the impulse counting system and the rest is to be used for accepting digital samples of the noise. Therefore, the computer has about 10 ms of the basic 20 ms cycle time in which to read all the 1 ms counters. During the last 8 ms all the 3 ms counters are also available for reading; and during the last approximately 1 ms all the 10 ms counters are to be read. The counters must be reset at some time before the 20 ms cycle begins again. The pulse-per-second counter, however, must accumulate pulses during 50 of these 20 ms cycles. Therefore, once per second the computer is sent a signal that tells it to sample and reset all the one-second counters.

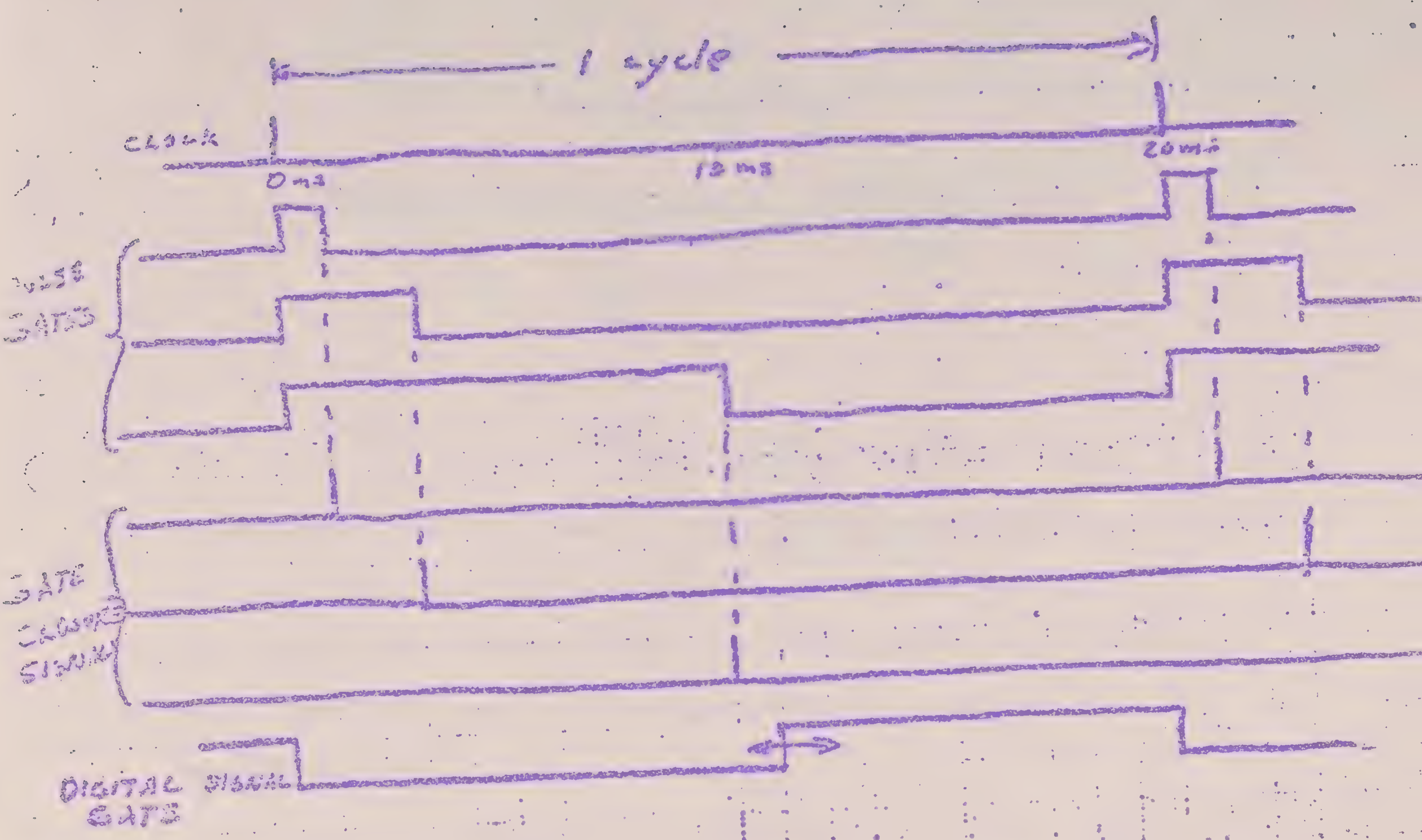


Figure 10

NOISE MEASUREMENT TIMING DIAGRAM

Whenever the computer reads one of the counters it increments by one the contents of the C array location indexed by the amplitude and the duration of the counter and by the number of pulses the counter has counted.

Each counter must be designed with a sufficient capacity to accept all the pulses that could possibly occur during the time interval that it will be gated open. We assume that at our maximum bandwidth of 40 MHz there will occur no more than 10^7 pulses per second. This dictates a counter size of 24 bits ($2^{24} = 16,777,216$); desired sizes for the other time intervals are indicated in Table IV

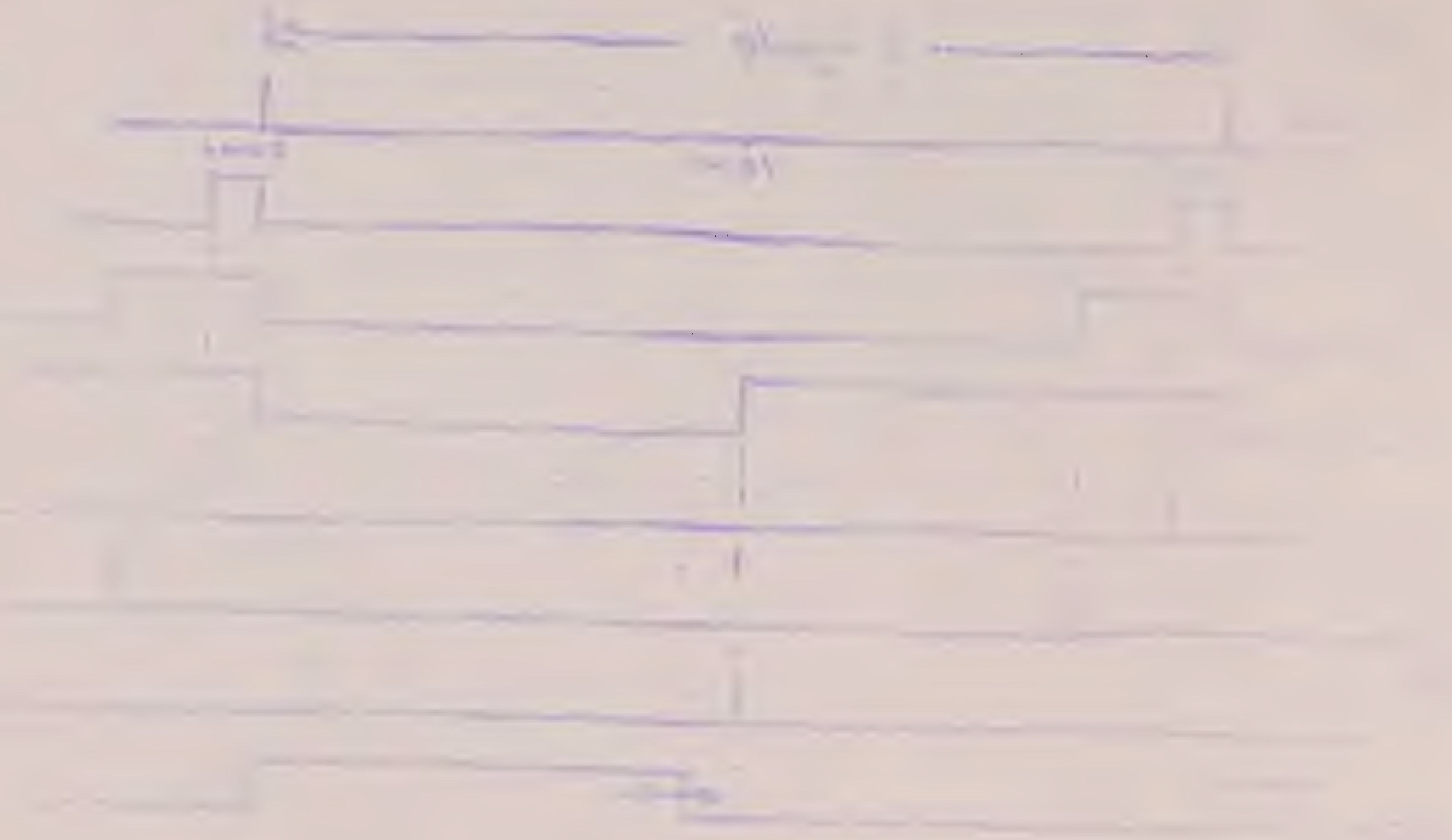


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Table IV

PULSE COUNTER SIZES

Interval	Pulses (Maximum)	Counter Size (Bits)
1 s	10^7	24
1 ms	10^4	14
3 ms	3×10^4	15
10 ms	10^5	17

but the actual sizes for these counters is still to be resolved in light of at least two other considerations, (1) the size of the counting array within the computer in terms of what is allowable and in terms of what is reasonable, and (2) the availability of counters of the appropriate sizes.

The computer will be called upon to read each of the short-interval counters 50 times per second and the one-second counters once per second. The number of counters is determined by L levels times 4 intervals and the number of bits per counter is still an engineering option.

d. Noise Sampling

To obtain the mean noise power and the ratio of rms to average noise voltage we will use the same A/D converter required by the propagation experiment and will sample and digitize the noise process. These digitized samples will be processed by the minicomputer to produce

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at least the two parameters mentioned above, and possibly to also provide the noise amplitude probability distribution (APD). Figure 7 indicates the receiver output being switchable between the A/D converter and the pulse measurement system and the timing diagram of Figure 10 shows the time slot allocated to the sampling of the noise. The minicomputer will receive its last gate closure signal at 10 ms and will output a digital signal gate as soon as it has finished reading and resetting all the counters. This gating signal will enable a pulse chain to operate the A/D converter at a rate of 10 thousand samples per second (see Figure 7) for a duration of perhaps 9 ms of the basic 20 ms cycle. The sampling gate will close just prior to the beginning of the next 50 pps clock pulse, thus completing a cycle. This will give us approximately 90 samples per cycle, 4500 samples per second, or about 2.7 million samples in a ten-minute data collection period. Immediately following the completion of a ten-minute sequence of measurements the computer will calculate the required parameters and print them on the system's teletype terminal.

2. Propagation

a. Overview

As discussed earlier the main part of the propagation measurement consists of trying to measure and characterize (1) the impulse response of the packet radio channel (2) the extent of time variability, and (3) the spatial variability. The directional properties (i.e., angular spectrum) of the received signal will be examined as well.

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at least the two parameters mentioned above, and possibly to also [illegible] (APD). Figure [illegible] shows the receiver output being switchable between the A/D converter [illegible] measurement system and the timing diagram of Figure 10 [illegible] the sampling of the noise. The [illegible] gate closure signal at 10 ms [illegible] it has [illegible] signal will [illegible] 10 thousand [illegible] of perhaps 9 ms [illegible] to the beginning [illegible]. [illegible] per second, [illegible] collection period. [illegible]

[illegible]

[illegible]

b. Channel Impulse Response

The method used to measure the channel impulse response will hinge upon the extent of time variability. To make that assessment we will operate briefly by recording the received pulse on a wideband oscilloscope. It will be viewed at the detector output following the surface wave demodulators. If the pulse-to-pulse variations are small enough, we will then proceed with the set-up shown in Figure 11.

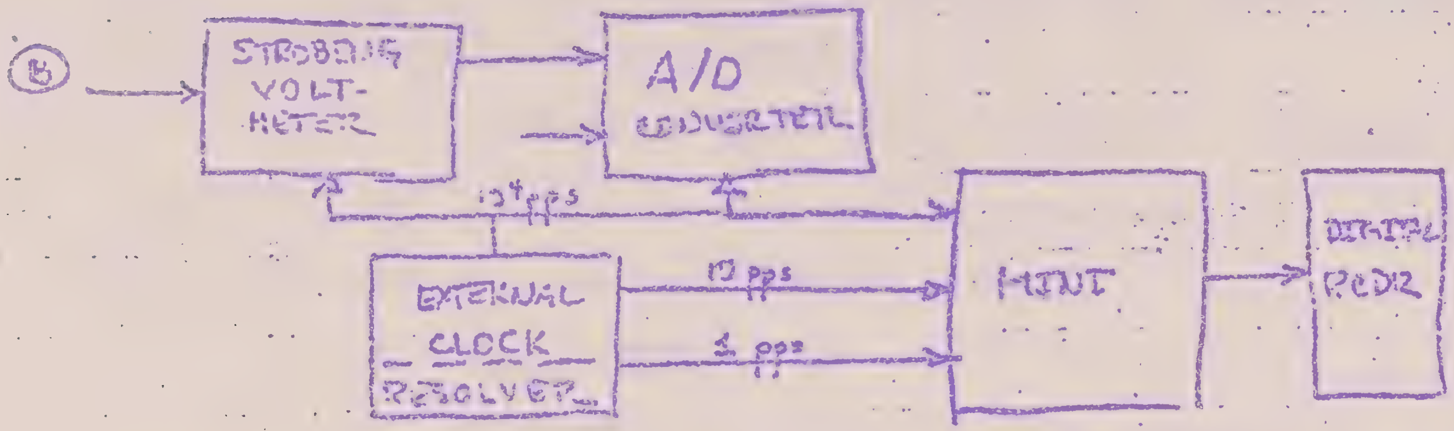

Figure 11 Conceptual Diagram of Impulse Response Recording System

This arrangement samples the pulse coherently by drawing one sample per received pulse in the manner of a sampling oscilloscope. Assuming a 40 MHz bandwidth and therefore an 80 MHz sampling rage, to reproduce the 10 μsec period containing the received pulse requires a minimum of 800 samples. If we instead obtain 1000 samples/pulse, a clock (sample) rate of 10^4 per second allows the synthesis of a "composite" pulse once each 100 ms. The A/D converter would most logically be 8-bit for compatibility with the 8-bit byte of the minicomputer and the 8-bit character recorded by the digital recorder. Furthermore, the resulting 48 dB dynamic range is more than adequate for the side lobes of the 127-chip spread-spectrum sequence. The minicomputer will provide the necessary preamble information as well

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as being a buffer of the input data. Output records will each consist of 5 to 10 composite pulses. The composite pulse will be processed off line for maximum-delay and shape descriptors.

If the channel variation becomes too great to be able to "compose" a received pulse by means of the above technique, we will resort to some form of analog recording with attendant reduction of bandwidth or to wider bandwidth digitizers that are either less accurate of if equally accurate, quite expensive.

A minimum of 2000 composite pulses will be recorded for each "terrain" type and frequency, however, various recording sites will be used within a given "terrain" category.

c. Time Variability

At first cut, we assume that moving automobiles provide the most important source of time variation. Consequently, we set the post-detection bandwidth at 200 Hz. This is slightly more than the shift expected from an auto moving at 30 m/sec when a 1.5 GHz frequency is used. Considering that the 2 sec required for an auto to pass is a reasonable record length, and using a sampling rate of 250 Hz per quadrature channel, we would obtain 500 complex samples per record. (Actually the record duration may be extended slightly to result in a 512-point data record.) Power spectra, computed off-line, will be used to characterize the time variation. Other presentations may also be computed as different models for the channel are considered.

A second type of narrowband data record may be taken that is directed toward measuring the channel at frequency spreads that would begin to affect a 100 kbps system. For example, tolerating no more than

a 36° phase shift per bit would permit Doppler spreads of less than 10 kHz. Tests will be made to determine the energy present at these larger spectral spreads but it is doubtful that the reflectors normally present would produce spreads of that order.

A block diagram of the narrowband digitizing and recording system is shown in Figure 12. It is anticipated that approximately 100 narrowband data records will be taken at various locations within a "terrain" category. This will allow a representative selection from which to calculate power spectra.

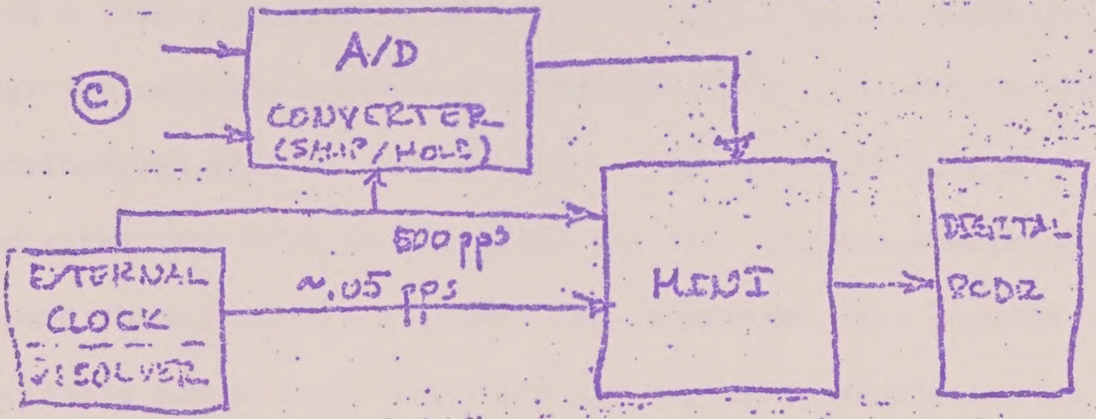

Figure 12 Conceptual Diagram of Narrowband Recording System

d. Space Variability

With a small amount of forethought the narrowband filters used in the fixed-terminal measurement may also be used here. If the record length and sample rate remain the same at 2 sec and 250 Hz per channel, respectively, then a 50λ spatial record requires vehicle velocities of 15 and 7.5 m/sec for 500 and 1000 MHz, respectively (33.6 and 16.8 mph). These are viewed as reasonable speeds for most measurements contemplated.

The time-consuming nature of this measurement will limit the number of data records to the order of 25 per "terrain" category.

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C. Off-Line Processing

Noise data taken as described earlier will be processed in real time. The suggested timing pattern is meant to be indicative of the rate at which data can be collected, processed, and output. We are of course prepared to alter the data rates somewhat to accomodate possible processing or I/O problems. Thus for noise measurements all output will be to the terminal.

The propagation measurement, on the other hand, will lead to considerable off-line calculation--perhaps on the same minicomputer but more likely on a larger general purpose machine with graphic capability. Of the propagation measures mentioned in Section II-B, only the threshold crossing distributions will be done on-line. The composite pulses recorded on digital tape will be processed off-line for the remaining impulse-response shape characteristics. The narrowband data records will be selectively transformed using FFT algorithms. Calculation of the spatial frequency spectra from the narrowband and time waveform will require a precise knowledge of the vehicle velocity used in the recording process.

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